Waste Gasification by Thermal Plasma: A Review

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Abstract This paper proposes an overview of waste-to-energy conversion by gasification processes based on thermal plasma. In the first part, basic aspects of the gasification process have been discussed: chemical reaction in gasification, main reactor configuration, chemical conversion performances, tar content in syngas and performances in function of the design and the operation conditions (temperature, pressure, oxidizing agent…). In the second part of the paper are compared the performances, available in the scientific literature, of various waste gasification processes based on thermal plasma (DC or AC plasma torches) at lab scale versus typical performances of waste autothermal gasification: LHV of the syngas, cold gas efficiency and net electrical efficiency. In the last part, a review has been done on the various torch technologies used for waste gasification by plasma at industrial scale, the major companies on this market and the perspectives of the industrial development of the waste gasification by thermal plasma. The main conclusions are that plasma technology is considered as a highly attractive route for the processing of waste-to-energy and can be easily adapted to the treatment of various wastes (municipal solid wastes, heavy oil, used car tires, medical wastes …). The high enthalpy, the residence time and high temperature in plasma can advantageously improve the conditions for gasification, which are inaccessible in other thermal processes and can allow reaching, due to low tar content in the syngas, better net electrical efficiency than autothermal processes.

Keywords *Allothermal process; Gasification; Syngas; Thermal plasma torch; Waste-to-Energy; tar content*

Introduction

Since the end of World War II, all developed countries generate more and more domiciliary and industrial wastes per capita at a level that is becoming unmanageable, causing permanent damages to the environment. For example, in Japan, it is estimated that each inhabitant produces around 1.1 kg/day of Municipal Solid Waste (MSW) and the total quantity is about 5.2×10^7 tons/yr. Moreover, total quantity of industrial waste is about 4×10^8 tons/yr [1].

Public and political awareness to environmental issues have led to plan to implement strategies for waste management. In parallel, the energy consumption continuously grow in the world due to the increasing population, the industrial development and the consumerism which has become a life standard in industrial countries.

The sustainable strategy for the waste management is to improve waste treatment in the aim to reduce their landfill disposal and minimize the environmental impact. For few years, wastes became one of the renewable resources that could play a major role in renewable energy [2]. Various thermal processes, like combustion, pyrolysis or gasification have been developed for treating these wastes in the aim to recover energy from the organic fraction [3-22]. Various thermal processes, like combustion [3-6], pyrolysis [3-7] or gasification [3-22], have been developed for treating wastes in the aim to recover energy from the organic fraction. In these papers, which are mainly reviews on the thermo-chemical conversion of biomass/waste to energy, are discussed the performances of the existing thermal processes, and more particularly the gasification processes, in function of the technologies used. However, waste gasification by thermal plasma, which is a relatively new technology in the field of waste treatment by gasification, is often forgotten or neglected in the literature and only few recent studies have analyzed the plasma process as a solution for Waste-to-Energy recovery [3, 4, 6, 8-10]. However, in these papers, the plasma technologies are often partially studied, so the main purpose of this present paper is to focus on the thermal plasma technologies for the treatment of municipal and industrial wastes for energy recovery.

There are numerous wastes with an organic content which may be suitable for gasification or other thermochemical processes. MSW is a heterogeneous fuel containing a very wide variety of solid wastes. Due to the presence of some post-recycling materials, such as paper fiber and plastics, its heating value can be high and gasification proposes to take advantage of this. The chemical composition of MSW can be compared to any solid organic fuel like coal or biomass. According to [23], the element composition of MSW is in the range (Weight %): C – (17 – 30), H_2 – (1.5 – 3.4), O_2 – (8 – 23), H_2O – (24 – 34), ashes – (18 – 43) and the average

specific combustion heat of MSW is in the range from 5 to 10 $MJ.kg^{-1}$. In [24, 25], thermal plasma pyrolysis of old tires has been tested and the combustion heat value of the produced gas was in the range 4 to 7 $MJ.Nm^{-3}$ in the first one and 5.3 to 7.9 $MJ.Nm^{-3}$ in the second one (up to 9 $MJ.Nm^{-3}$ with water gas shift reaction).

This paper reviews the current status of thermal plasma technologies for the treatment of domiciliary and industrial wastes for energy recovery. The inorganic waste plasma treatments by melting and vitrification are not discussed here and are not addressed in this review [26-31].

In the current context of conventional fossil resource depletion, global warming and rising waste, gasification of wastes appears as an interesting alternative compared to combustion processes. Indeed, the usual methods based on the incineration of wastes are low energy balances for electricity production. Net electrical efficiencies from 18 % to 22 % can theoretically be achieved at an industrial scale, resulting from the use of a boiler associated with a steam turbine [16]. In opposition, gasification by thermochemical decomposition of organic material allows the production of synthesis gas, i.e. syngas, in which one can recover up to 80 % of the chemical energy contained in the organic matter initially treated. Based on these performances, a plasma gasifier associated with a gas turbine combined cycle power plant can target up to 46.2 % efficiency [32]. Moreover, this synthesis gas produced by gasification, mainly composed of CO and H_2 can also be used as feedstock for the production of synthetic liquid fuels in processes such as Fischer-Tropsch process.

However, conventional methods based on autothermal gasification present some limitations that might be overcome through plasma [33], particularly in terms of: material yield, syngas purity, energy efficiency, dynamic response, compactness and flexibility. Injected plasma power can be adjusted independently of the heating value of the treated material.

On the chemical aspect, the thermal plasma can advantageously contribute to the gasification by accelerating the kinetics and improving high temperature cracking of impurities in the syngas produced. On the thermal aspect, enthalpy provides by the plasma can easily be adjusted by the tuning of the electrical power supplied to the system, making the process independent of the ratio O/C and the nature of the plasma medium (neutral, oxidizing or reducing atmosphere), contrary to the autothermal gasification processes.

Gasification process

Gasification process was discovered in 1699 by Dean Clayton [34]. It was implemented during the nineteenth century in factories for producing town gas. The first gas plant was established in 1812 in London. With the discovery of the Fischer Tropsch Process in 1923 by Franz Fischer and Hans Tropsch, it became possible to convert coal to liquid fuel. During World War II, German army needed to improve the use of the gasification process for fuel and chemical production. The end of the war and the availability of cheap fossil fuel reduced the usefulness of this process but with the current context of conventional fossil resource depletion and the increasing of fuel prices, gasification of wastes appears as an interesting alternative for energy.

Gasification is an incomplete oxidation of organic compounds after a pyrolysis decomposition step. The oxygen contained in the oxidizing agent used for the gasification (Air, oxygen, CO_2 or steam water) reacts with carbon to achieve a combustible gas, called "syngas". This syngas is mainly composed of carbon monoxide (CO) and hydrogen (H_2) with low quantities of carbon dioxide (CO_2), water (H_2O), methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH_3), and under certain conditions, solid carbon (C), nitrogen (N_2), argon (Ar) and some tar traces. Nitrogen and argon coming from the use of air as the reactant or are due to their use as plasma gas.

This synthesis gas produced can be used as feedstock in: (i) Fischer-Tropsch process for liquid fuel production [35], (ii) gas turbine or fuel cell for electricity production [36-38] or (iii) chemicals products as ammonia, methanol and hydrogen [39].

Chemical reaction in gasification

The waste conversion into syngas involves complex chemical reactions. Heterogeneous reactions take place in gas-solid phase while the homogeneous reactions occur in gas-gas phase. The main chemical reactions of gasification occurring after the pyrolysis of the wastes are given as followed in Table 1 [3, 9]:

The homogeneous reactions (reactions 9-12) are almost instantaneous in high temperature conditions in contrast to heterogeneous reactions (reactions 1-8).

A very large number of gasification reactions take place in the reactor but we can differentiate three of them which are independent gasification reactions: Water-gas reaction (6), Boudouard reaction (7) and hydrogasification (8). In the gas phase, these reactions can be reduced to only two: Water-gas shift reaction (11) which is the combination of the reactions (6) and (7) and methanation (12) which is the combination of the reactions (6) and (8).

It is important to notice that all these gasification reactions, except the oxidation ones, are equilibrium reactions. The final composition of the crude syngas will be determined by reaction rates and also by the effect of catalysts which is important for tar decomposition in the reactor, rather than by the thermodynamic equilibrium [9].

Main reactor configuration

There are presently several tens of different gasification processes which differ by the configuration of the reactors. These different configurations are fully described in numerous books and scientific papers [8, 36, 40, 41]. The main different reactor configurations are: Downdraft Fixed Bed, Updraft Fixed Bed, Bubbling Fluidized Bed, Circulating Fluidized Bed, Entrained Flow, Rotary Kiln, Moving Grate… These different configurations have been analyzed and commented in [9] and the main conclusions are as follows: It is commonly accepted that the three main reactor configurations are updraft, downdraft and fluidized bed.
Reed [42] gives the following description for each configuration:
In **updraft gasifiers**, the wastes are fed by the top of the reactor. The oxidizing agent, which may be air, oxygen, CO_2 or steam, is fed by the bottom of the reactor. The gasification reaction takes place in the bottom of the reactor between the downcoming material and the ascending gas. The reaction temperature is between 1 300 K and 1 700 K. The rise of the hot gas starts waste pyrolysis at lower temperatures and dries it. The tar levels in the crude gas with this reactor configuration are between 10 % and 20 %, which makes them difficult to clean for electricity applications.
In **downdraft gasifiers**, the wastes are fed by the bottom part of the reactor with the oxidizing agent, which may be air, oxygen, CO_2 or steam. The major part of the tars is burned for the pyrolysis of the wastes. This process is called "flaming pyrolysis". Thus, the tar levels in this reactor configuration are very low, around 0.1 %, as the major part of tars is burned to supply the energy for the pyrolysis / gasification reactions of the wastes. This reactor configuration is particularly suitable for the production of clean gas requiring low post-treatment for their use in electricity production with gas turbines. However, the operation generally requires a long residence time (1 h to 3 h) [41]. This configuration is considered most attractive to small units of 80 kWe-500 kWe and has the disadvantage to have low energy efficiency but with low tar concentrations [34].
In the case of **fluidized bed gasifiers**, the oxidizing gas allows the suspension of the treated waste. In this configuration, there is a mixture of the two phenomena identified previously in

the updraft and downdraft reactors. Thus, the tar rate is at an intermediate level between the updraft and downdraft reactors, between 1 % and 5 %. Gasification reactions are homogenized by suspended grounded wastes in the reactor. This method optimizes the temperature along the reactor and has a high reaction rate for short residence time (less than 30 min). The disadvantage of this configuration is the high proportion of particulates (tars) in the exhaust gas that requires high gas treatment and has low mass and energy yields [34].

Chemical conversion performances

Different criteria are frequently quoted for gasification processes. In order to compare different processes, we define energy efficiency (also called cold gas efficiency), H_2 rate and CO rate as follows (Equations 14 to 16). Cold gas efficiency is the energy produced by syngas combustion divided by the energy produced by direct combustion of product incremented by the added energy (electric or fuel) for allothermal processes. This efficiency does not take into account the steam consumption and electricity (related to pure oxygen production), or heat recovery by cooling synthesis gas (steam).

Fuel gas production is the flow of the gas mixture produced by gasification per kilogram of product treated in the reactor. When air is used as oxidant in the reactor, we can use, in this particular case, the formula [15]:

$$Fuel\ \ gas\ \ production\ \left(Nm^3.kg^{-1}\right)=\frac{air\ \ flow\ rate\ \ (Nm^3.s^{-1})\times 0.79}{\left[1-\left(CO+CO_2+H_2+CH_4+C_2H_2\right)/100\right]\times\ feeding\ \ rate\ (kg.s^{-1})} \quad (13)$$

In (13), fuel gas production is function of the ratio of the nitrogen at the entrance of the process to the nitrogen in the mixture produced. In this particular case, which cannot be applied for all gasification situations, it is assumed that the conversion is total (no oxygen gas in the crude gas) and the only gases produced during gasification are CO, CO_2, H_2, CH_4 and C_2H_2. In this case, the waste used as feedstock is only composed of C and H (no chemical species like S, Cl …).

Energy efficiency

Energy efficiency of the process (or cold gas efficiency) is defined by the ratio of the Lower Heating Value (LHV) of cold gas to the LHV of the waste treated, incremented by the added

energy (electric or fuel) for allothermal processes per kg of waste. It is defined by the following expression:

$$\eta = \frac{LHV\ of\ cold\ gas\ (kJ.Nm^{-3}) \times fuel\ gas\ production\ (Nm^{3}.kg^{-1})}{LHV\ of\ waste\ treated\ (kJ.kg^{-1}) + allothermal\ Power\ (kW) / waste\ flow\ rate\ (kg.s^{-1})} \quad (14)$$

In the particular case of waste gasification by thermal plasma, we have to take into account the origin of the electric energy consumed to create the plasma. If the electric energy comes from the electric energy generated by the process, the allothermal power is equal to the electric energy consumed to create the plasma. If the electric energy comes from a primary thermal power plant, the Allothermal Power = P_{Plasma}(electrical) / (Conversion efficiency of the thermodynamic cycle -Carnot-). Generally, the conversion efficiency of thermal power plant is between 30 % and 40 % for a single cycle steam power plant and can be up to 60 % for a Combined Cycle Gas Turbine (CCGT) power plant.

H_2 and CO yields

H_2 yield is defined by the ratio of the mass of hydrogen in the syngas produced per the mass of hydrogen introduced. For the CO yield, it is the ratio of the mass of carbon atoms in the CO produced per the mass of the carbon atoms injected. These ratios are given by the formulas [43]:

$$H_2\ yield = \frac{H\ atoms\ in\ the\ syngas}{H\ atoms\ injected} \quad (15)$$

$$CO\ yield = \frac{C\ atoms\ in\ the\ \ formed\ CO}{C\ atoms\ injected} \quad (16)$$

It is important to keep in mind that the H_2 rate in the crude syngas is strongly linked to the oxidizing agent injected and/or the moisture content in the waste treated. As H_2 yield is not representative of the conversion rate of the processes, only the CO yield can be used to provide good information on the mass balance and on the performances of the gasification processes.

Tar content in syngas

This new interest for gasification was accompanied by an expansion of devices based on the syngas exploitation associated with waste gasification, like internal combustion engines (ICEs), gas turbines or fuel cells.

Tar presence in syngas is the most problematic parameter in any industrial gasification processes. This could have important implications in the design and the operation of gasifiers to ensure adequate control of reaction conditions. These tar constituents can be used as indicators of overall reactor performance and design [44].

Tars are complex mixture of condensable hydrocarbons or organic compounds having a molecular weight higher than benzene C_6H_6. This definition was introduced by the tar protocol measurement at the IEA Gasification Task meeting at Brussels in 1998 [45]. The tar rate is representative of the quantity of tars mixed with the syngas after gasification of the organic material ($g.m^{-3}$).

The differences in tar nature and quantities are mainly function of the processing conditions, the applied technology and the nature of the wastes to be treated.

In his survey of biomass gasification, Reed [42] already concluded in 2001 that the Achilles heel of biomass gasification is the amount of tars contained in the syngas produced (0.1 – 10 %) and the technical feasibility and economical viability of biomass gasifier at an industrial scale will be strongly linked to the performances of the cleaning processes.

Depending on applications focused, tar concentrations in the syngas have to be mastered or cleaned. The scientific literature contains many data on the tar reduction, conversion and/or destruction in waste gasification processes. More than 400 papers have been referenced by Milne [46].

They focused on tar removal through physical processes and “tar” conversion through thermochemical and catalytic processes (Thermal, steam, partially oxidative, catalytic and/or plasma processes). The choice of the cleaning process depends specifically on the applications referred.

Tar levels from gasifiers

The results reported from the literature for tar rates, from the three main categories of gasifiers, are summarized in Table 2, showing a wide range of values, within each case (updraft, downdraft and fluidized bed) some ranges spanning from one to two orders of magnitude [46].

There is a general agreement on the relative order of magnitude of tar rates in function of the gasification process. They can be classified as follows: updraft gasifiers being the “dirtiest”, downdraft the “cleanest” and fluidized beds intermediate with an average value for updraft reactor at 100 g.Nm^{-3}, fluidized beds at 10 g.Nm^{-3} and downdraft reactor at 1 g.Nm^{-3} [46].

Any kind of material can be used as feedstock if it contains a certain amount of organic material inside (MSW, used tires, paper mill waste, plastic waste, liquid and solid hazardous waste, Refuse Derived Fuel (RDF, i.e. mixture of plastics, paper, wood and dried organic material), medical waste, biomass wastes …).

The choice of the gasifier technology will depend of several fuel requirements like the particle size, the morphology, the moisture content, the ash content, the ash melting point, the bulk density, the temperature profile in the gasifier, the heat exchange, the residence time, the conversion efficiency, the process flexibility… The limitations and the categories of the materials used as feedstock in gasifier have been already studied and discussed in several papers, more particularly in an excellent review by Arena [9] in which are well summarized all the fuel requirements in function of the gasifier technologies.

Tar tolerance of End-Use Devices

A very important topic is the tar tolerance of the end-use devices. Many data are available from R&D activities and from field experience, mainly coming from manufacturers.

Depending on the applications referred for energy and chemicals production, the tar tolerance thresholds estimated are listed below [46]:

- Stirling Engines and turbines can work with raw gas (External combustion). No cleaning of the syngas is necessary for these applications but the energetic yields of these devices are low (around 20 %).
- Compressors accept a tar limit between 100 mg.Nm^{-3} and 500 mg.Nm^{-3}. This option is interesting for the syngas storage but depending on the end-use of this gas, a subsequent processing of the syngas for cleaning will be mandatory.
- The internal combustion engines tolerate a maximum tar concentration of 50 mg.Nm^{-3} for the lightest compounds and 5 mg.Nm^{-3} for the heaviest, and a concentration in solid particles lower than 30 mg.Nm^{-3}.
- Gas turbines have a maximum tar tolerance much lower; no more than 0.5 mg.Nm^{-3}. Concerning the solid particles maximum rate in the gas turbines, we didn’t have confirmed

data but we can assume that it is in the same order of magnitude that for the Fischer Tropsch process.

- The Fischer Tropsch process requires tar concentrations below 0.1 $mg.Nm^{-3}$ and a concentration in solid particles lower than 0.02 $mg.Nm^{-3}$.

In the major part of these applications, an external treatment of the crude syngas is mandatory in the aim to have a syngas as pure as possible.

Tar destruction

Tar condensing at low temperature, their presence in the crude gas is a technological problem for the gasifiers. However, this problem is not significant, as such all tars are at a temperature sufficient to be in gas phase but it is mandatory to process tars in function of the end-use.

The tar destruction can be divided into two methods: primary (inside the gasifier) and secondary (downstream of the gasifier) methods. The primary methods are more interesting because the thermodynamic efficiency losses associated to the gas cooling for its purification can be minimized. The ideal method is to use only the primary method [12].

Primary methods

The primary methods are tar treatment inside the gasifier at high temperature. The main solutions proposed in the scientific literature are to optimize the design of the gasification reactor, its operating parameters (temperature, pressure, oxidizing agent/waste ratio, residence time …), by adding catalyst or by plasma treatment [46-57]: The gasification temperature (> 1 200 K - 1 300 K) has a beneficial effect to minimize the tar quantities and allows destroying the aromatics without a catalyst [47, 51]. A reduction of more than 40 % in tar yield has been reported when the temperature was raised from ~ 1 000 K to ~ 1 200 K. Preheating the gasification agent has the advantage to significantly reduce the tar content, due to the thermal decomposition at high temperature [50]. About the residence time, Kinoshita et al. [52] concluded that it has a little influence on the tar level, but it has significant influences on the tar composition. About the oxidizing agent/waste ratio, it is observed the decrease in tar yield by increasing this ratio [49]. Gasification can operate under atmospheric to high pressures. High pressures are preferred to directly connect the gas produced to downstream processes such as Fischer-Tropsch process (operating pressure around 30 bar), or gas turbines and synthesis of chemical products (up to 80 bar) [58]. To significantly reduce the energy

consumption in compression stages, gasifiers need to be sized at a pressure allowing the direct supply of syngas downstream units. It is preferable to compress the incoming agent such as reactant and product, than compress the gas output. According to [58], total energy spend in a coal gasification process is 22 MW at 5 bar and 5 MW at 50 bar for a gas production of 100,000 $Nm^3.h^{-1}$. The use of high pressure in the gasifier allows reducing the reactor size, to the detriment of their thickness, and heat losses in the compressor. However, increasing pressure favors the production of methane at low temperature [59], but becomes negligible at temperatures higher than 1 800 K.

Catalysts like dolomite, limestone, olivine sand, bauxite, lanthanum, alumina, nickel aluminate, cobalt, natural clay minerals and iron minerals can be used to optimize the tar reforming at high temperature [46, 53-57]. It is an efficient method for the tar destruction but this primary method can be very expensive in function of the catalyst used and its consumption.

Secondary methods

Secondary methods suggest a cleaning downstream of the gasifier. Although the primary methods are the most important, the combination with downstream methods can be necessary in function of the tar destruction level requested. There are basically five systems of elimination of tars: thermal cracking, catalytic cracking, mechanical methods (scrubber, filter, cyclone, electrostatic precipitator …), self-modifications (operating parameters) and plasma methods [12, 48].

Thermal and/or catalytic cracking is preferably used when the temperature of the gasifier does not allow the processing of tars by the primary methods ($T < 1\ 200$ K). The cracking of tars by cold plasma in series with gasification reactor has been studied and several groups have demonstrated with success that organic elements (tars and particles) can be easily decomposed by corona discharges or by gliding-arc [48, 60-63]. The role of the plasma treatment is twofold: it allows, on the one hand, a significant purification of gas by limiting the production of tars and on the other hand, producing a synthesis gas enriched in hydrogen (water-gas shift reaction). Plasma methods have also the advantages to be able to operate at high temperature and to be retrofitted to existing installation.

The tar removal by secondary methods is one of the most concern topics for current scientific research and numerous treatment methods regularly emerge from the scientific community

and are reported to be very effective in tar reduction but still need to be optimized to be economically viable and used industrially [46, 47].

Rabou et al. [51] preconize a residence time of 4s for the thermally conversion of 97 % of tar in a dense fluidized bed at 1 450 K. Fourcault et al. [64] demonstrate the influence of plasma parameters on the tar destruction with a small influence on the concentration of synthesis gas. Gasification by thermal plasma gives good results in terms of gas purity and energy efficiency. The main difference from conventional methods comes from the tar concentration at the output of these processes. Thus, the autothermal methods provide tar content exceeding 1000 $mg.m^{-3}$ while it is on the order of 1 $mg.m^{-3}$ for plasma processes. The tar contents at the output of a gasification stage by thermal plasma are 1000 time less than that obtained by autothermal fluidized bed [46]. These results can be very interesting for an application of synthesis gas in second generation biofuel that requires tar concentration below 0.1 $mg.m^{-3}$. However, to reach this threshold concentration, the purification of syngas is mandatory but will be less costly. According to Göransson et al. [12], the drying of the hot gas under high pressure can provide a highly effective removal of contaminants. This technique still requires the use of high pressures to reduce heat losses in the compressor.

Thermal plasma gasification processes

Allothermal gasification processes requires external energy source which can be of different nature: external pre-heating of the reactor by combustion, electrical energy, solar energy…

Considering the performances, it appears from literature than plasma seems to be one of the most probative technologies for waste gasification. In this review, only the allothermal gasification processes based on high temperature plasma have been studied.

However, plasmas technologies applications are not recent. Plasmas processes have been used and developed during the nineteenth century by the metalworking industry to provide extremely high temperatures in furnaces. During the early twentieth century, plasma processes were used in the chemical industry to manufacture acetylene from natural gas. Since early 80's, plasma technology is considered as a highly attractive route for the processing of MSW and successful applications in treatment of hazardous and harmful materials such as asbestos, radioactive waste vitrification and chemicals have showed the maturity of this technology [23-29, 65-70].

Advantages of the plasma technology

Knoef [34] shows the differences obtained in autothermal processes in function of the oxidant used (pure oxygen or air). Pure oxygen provides a gas with a low calorific value of 10.1 $MJ.m^{-3}$ while the use of air gives only 4.2 $MJ.m^{-3}$ due to the dilution of the synthesis gas with the nitrogen introduced with the air flow. Although, using a high flow rate of pure oxygen is expensive for an industrial process. Steam water is generally preferred because it produces the desired reactions including the steam reforming reaction and increases the H_2 ratio in the syngas. However, the steam reforming reaction is highly endothermic and need high temperature (1100 K-1700 K). One solution is to use a dual fluidized bed reactor. This reactor is designed to separate the gasification from the combustion. The high temperatures are conveyed between the two reactors with sand. The interest of this technology is to prevent syngas dilution by the nitrogen of the air and the combustion of the wastes by separating the gasification from the combustion. The high temperature obtained in the reactor without using the combustion process allows producing a synthesis gas with high purity and high calorific value.

Autothermal processes involve chemical reactions known as redox. These reactions establish high temperatures in the reactor but the maximum temperature possible by combustion is 3000K [31] (for acetylene-oxygen mixture) while it is possible to achieve gas temperature up to 15 000K with a thermal plasma [71]. Such a temperature in plasmas can allow synthesizing or degrading chemical species in some conditions unreachable by conventional combustion and can greatly accelerate the chemical reactions. Thermochemistry of combustion does not allow precise control of the enthalpy injected into the reactor. Plasma process allows an easiest enthalpy control by adjusting the electrical power. The reactive species produced by the plasma, such as atomic oxygen and hydrogen or hydroxyl radicals, is an additional advantage for the use of plasma. In the literature, it is reported that these species enhance strongly the degradation of the tars with greater efficiency than conventional processes [72, 73].

Only dual fluidized bed or allothermal processes can allow producing syngas without nitrogen dilution. Nevertheless, dual fluidized bed produces high tar content, mostly above 10 $g.Nm^{-3}$ [12].

These technical limitations lead to consider the plasma technology as one of the best alternative approaches to produce high purity and high LHV syngas.

Plasma torch configurations in the reactor

In a first configuration, the product is injected close to the plasma plume. This method is the most studied in the literature with scientific experiments in China [25, 73-76], Taiwan [77], France [78], Czech Republic [71, 79-84] and Russia [85-87]. The product can be injected in solid form [71] or liquid [78], from a pyrolysis cycle or crushed. The torch is often located in the upper part of the reactor with an ash recovery area in the bottom part [32, 81].

In a second configuration, plasma torches are close to a molten bath. Indeed, only inorganic compounds form a melt. However, these technologies are mainly used for treatment of industrial wastes like asbestos or radioactive waste [88]. Steam is injected in the treatment zone to obtain gasification reaction. At the reactor output, other steam injection allows to stop the chemical reactions by quenching. Moreover, steam helps to adjust the H_2/CO ratio by the water gas shift reaction.

A final thermal plasma configuration process is a hybrid process, incorporating plasma technology combined with incineration or some other thermal processing technology, usually allows better use of the heating value of the waste material. This configuration, which cannot be considered purely as a thermal plasma gasification technology, is a thermal plasma treatment of gases leaving the reactor. This treatment technique is used in the plants of CHO power, Plasco Energy group, AlterNRJ. In this case, thermal plasma allows the tar treatment of the syngas at the exit of the gasification reactor [64]. The pyrolysis zone (autothermal zone) is separated from the reduction zone (plasma zone). This configuration is similar to a two-stage gasifier design which is reported to be very effective in producing clean gas [41]. In [89], they concluded that the tar content was 40 times less with a two-stage gasifier (about 50 $mg.m^{-3}$) than with a single-stage reactor under similar operating conditions.

Waste gasification by plasma process at lab scale

In this part of the review are compared the performances of various waste gasification processes based on thermal plasma represented in the scientific literature. Thermal plasmas can be obtained by arc discharges (DC or AC plasma) or by Radio Frequency (RF)-MicroWave (MW) plasma. RF or MW plasmas don't have electrode erosion but have low energy efficiency, about 40 % to 70 % (60 % to 90 % for arc torches) [73]. From this review, it clearly appears that the main plasma torch technology applied to waste gasification is the DC technology which is used in all the studies excepted in [32, 85, 90] where an AC plasma torch is used.

A wide range of organic wastes treated by plasma process has been studied: MSW [9, 23, 66, 91-94], used tires [24, 25, 73, 75, 85], paper mill waste [95], plastic waste [73, 74, 96, 97], liquid and solid hazardous waste [98-101], Refuse Derived Fuel (RDF, i.e. mixture of plastics, paper, wood and dried organic material) [67, 85, 86], medical Waste [66, 73] and biomass wastes [32, 66, 71, 73, 76, 77, 81, 85, 90, 102-104].

In [66], one can notice that the H_2 and CO yields are strongly linked to the original composition of the waste treated and can vary, with the same experimental conditions, from 49.4 vol% to 64.4 vol% for H_2 and from 24.8 vol% to 36 vol% for CO in function of the nature of the waste. It is important to keep in mind that the H_2 and CO rates in the crude syngas is strongly linked to the oxidizing agent injected and/or the moisture content in the waste treated. In most of the cases, the results given by authors don't take into account the nitrogen and the water included in the crude syngas. Moreover, the temperature of exhaust gas, the pressure, the waste flow rate injected, the oxidizing agents such as steam or air are rarely expressed with precision. All these lacks of information make it difficult to accurately determine the influence of the plasma on the syngas product.

Based on this review, it cannot be concluded on the best effective configuration from the different experimental results which are strongly linked to the reactor used and the elementary composition of the waste treated. However, the performance and composition of synthesis gas differs significantly depending on the method applied and gasification parameters as follows:

- the elementary composition of the waste (carbon, hydrogen, oxygen, moisture, mineral elements)
- the LHV of the waste
- the nature of the oxidizing agent (air, O_2, CO_2, steam)
- the amount of injected oxidant (water gas shift reaction increases the rate of hydrogen)
- reactor pressure
- the temperature gradient within the reactor
- the scale effect and heat losses as a function of the refractory material of the reactor
- the quality of the post-treatment of the crude syngas
- the influence of pretreatment of the product before the injection
- the mix of the waste with a fossil fuel (coal powder) to optimize the temperature and the reactions

On plasma technology must be added the nature of the plasma gas (Ar, N_2, H_2O, H_2, CO, CO_2…), the specific enthalpy, the diffusion rate of plasma, the injected power, the thermal efficiency of the plasma torch and the technology of the plasma torch (DC, AC or RF).

Considering relevant performances, it appears clearly from literature than plasma appears to be one of the most probative technologies for waste gasification. Determinant performances are the CO and H_2 yields, the cold gas efficiency (energy efficiency), the gas calorific value (LHV) and particularly, the tar content. This last information is often neglected by the authors and is only available in specific studies based on the post-treatment of the tar in a second step of the processes by primary or secondary methods.

Due to the absence of complete results in the scientific literature, only few representative plasma gasification processes have been compared [25, 32, 74, 81, 85, 92, 94].

In Table 3 are summarized the main results on plasma gasification processes and are compared to typical ranges of variations of some operating and process performance parameters in autothermal gasification of MSW [9].

These results give tendencies about the efficiency of allothermal processes. The main conclusion is that allothermal gasification (DC or AC torch) allows processing all kind of wastes by adjusting the energy input with the plasma, independently of the oxidizing agent ratio, the LHV and the moisture of the waste. The LHV of the cold gas is function of the nature of the waste treated and the nature of the oxidizing agent but for the different studies, independently of these parameters and the plasma technology used, the energy efficiencies are in the same order of magnitude and are comparable to the typical range of energy efficiency in autothermal gasification.

About the comparison of allothermal versus autothermal gasification processes, the main difference is on the net electrical efficiency (15 % - 24 % for autothermal and 26 % - 49 % for allothermal) which is based on the theoretical electrical conversion performances of the end-use devices which are strongly dependent of the tar content in the syngas, key parameter for the performances of the overall process.

The high enthalpy, the residence time and high temperature in plasma can advantageously improve the physical conditions for gasification, which are inaccessible in other thermal processes and can enhance strongly the degradation of the tars and allow reaching, due to low tar content in the syngas, better net electrical efficiency than autothermal processes.

Best performances have been obtained by Rutberg and al. [32] who have studied, experimentally (plasma process) and numerically (autothermal versus plasma), the gasification of wood residues with different oxidizing agents (Air, O_2, CO_2, H_2O and mixture of these oxidizing agents). The results show the benefit of the allothermal plasma process versus the autothermal process with the adding of an oxidizing agent. Experimentally, the best results are that from 1 kg of wood residues with a moisture of ~ 20 % (LHV = 13.9 $MJ.kg^{-1}$),

it is possible, by plasma gasification with air as oxidizing agent, to generate ~ 13.5 MJ of chemical energy with an energy consumption of ~ 2.16 $MJ.kg^{-1}$ (plasma) and allows to generate ~ 8.58 $MJ.kg^{-1}$ of electric energy. The energy efficiency is ~ 84 % and the net electrical efficiency is ~ 46.2 %. This net electrical efficiency is based on the fact that the energy consumption of the plasma (2.16 $MJ.kg^{-1}$) comes from the 8.58 $MJ.kg^{-1}$ of electric energy generated by the process ((8.58 - 2.16) / 13.9 = 0.462). These results have been obtained experimentally with a lab-scale 3 Phase AC plasma torch whose the characteristics have been fully detailed in numerous papers [32, 85, 86, 105-112]. In their theoretical study, they indicate that the incorporation of CO_2 or H_2O in the plasma gasification of wood residues has the advantage to perfectly control the H_2/CO ratio in the output gas.

Overview of waste gasification by plasma process at industrial scale

The current market for high power plasma torches is mainly shared by four companies: Westinghouse, Europlasma, Tetronics and Phoenix Solutions Company (PSC). The technologies developed by Westinghouse [8, 113, 114], Europlasma [78, 92, 115] and PSC [116] are based on transferred and non-transferred DC torches with water-cooled metal electrodes while Tetronics torch [117, 118] is based on a transferred DC torch with two graphite electrodes not water cooled. Advanced Plasma Power (APP) and Tetronics have a collaboration agreement for the development and commercialization of plasma gasification WTE plants based on the technology of transferred DC torch [119]. For Westinghouse and Europlasma, their strategy is different since they have each developed a plasma gasification WTE process based on their own DC torch technology and market turnkey plants through subsidiaries (Alter NRG for Westinghouse and CHO-Power for Europlasma, respectively) [120, 121]. In parallel of these developments of industrial plasma gasification WTE plants, some companies also develop their own facility based on Westinghouse, Europlasma or PSC DC Torches (such as Plasma Arc Technologies, Plasco Energy Group, Enersol Technologies, Bellwether Gasification Technologies, Startech Environmental, Green Power Systems, Hitachi Metals …) [122-127] or on home-made torches (PEAT, InEnTec, Pyrogenesis …) [128-130]. Often, there is very few information on home-made torch technologies developed but it seems to be mainly based on DC torches. Although not yet validate for the waste gasification at an industrial scale, other plasma torch technologies (RF and AC) are being developed at a pilot scale in several research laboratories such as Applied Plasma

Technologies (USA), PERSÉE - MINES ParisTech (France) or Institute for Electrophysics and Electric Power - Russian academy of sciences (Russia).

Among the various gasification waste-to-energy processes at industrial scale, it follows two main configurations for the location of the plasma torches in the reactor which are mainly based on the waste to be treated. For the gasification of waste with low organic matter content, it is necessary to treat the waste at high temperature in order to melt the inorganic part. The products obtained are syngas from the organic part of the waste and slag from the non-organic part of the waste. In this case, the plasma torches are placed in the reactor body closest to the molten bath and the torches are non-transferred arc or transferred arc (the bath playing the role of anode for the plasma torch). In the case of waste with a high proportion of organic matter, it is not necessary to raise the temperature of the reactor above 1 800 K and in this case, the waste gasification in the reactor can be made either by autothermal or allothermal ways (plasma, dual fluidized beds ...). In this case, the plasma torch is placed at the outlet of the gasification reactor before the cooling of the crude syngas in the aim to treat the tar content in the syngas at an optimized energy cost (primary method).

In the last part of this study are detailed the various technologies of high power plasma torches, their levels of development, their gasification efficiency and the current status of waste plasma gasification plants in the world.

DC Torches

Westinghouse [114] is an American company created in the 1970s. The first R & D on the application of plasma began in partnership with NASA on the development of plasma torches to recreate and simulate the entry conditions in the atmosphere of the probes of the space program “Apollo”. It is only in the 1980s that the use of the torches has evolved to the waste treatment at high temperature. Currently, the company markets several torches, offering a wide range of power from 5 kW to 2400 kW. In the Table 4 are described the main characteristics of the Westinghouse DC torches [114]. These torches generally operate in non-transferred arc and can use different plasma gases: air, oxygen, nitrogen...

Europlasma is a French company created in the 90s by EADS-LV (Formerly Aerospatiale) [115]. Like Westinghouse, this technology was originally developed for space and military applications before developing applications related to the steel industry and the recovery and waste treatment. Today, the company markets a wide range of DC plasma torches (Table 5) whose powers range from 80 kW to 4000 kW depending on the type of application (gas

treatment, waste and biomass gasification (CHO-Power, subsidiary of Europlasma) [121], asbestos destruction (INERTAM, subsidiary of Europlasma) [131].

DC Plasma torches developed by Europlasma are very similar to Westinghouse torches.

A peculiarity of the Europlasma system is linked to the upstream electrode which is surrounded by a coil which generates a magnetic field. This allows controlling the movement of the extremity of the arc at the upstream electrode. At the downstream electrode, the arc movement is governed by the gas flowing into the injection chamber. The electrodes are cooled by a deionized water pressurized system.

Phoenix Solutions Company (PSC) is an American company created in 1993 (formerly FluiDyne Engineering Corp.) [116]. FluiDyne, after 40 years at the forefront of aeronautical and aerospace researches, was reformed as PSC in 1993 and became, in 20 years, one of the largest suppliers of plasma heating systems in the world. Today, the company markets a wide range of DC plasma torches (Table 6) whose powers range from 50 kW to 3000 kW and can operate on different plasma gas (air, N_2, O_2, H_2, CO or CO_2). Their plasma torches are used in several plasma gasification WTE plants [8, 124-127].

The Tetronics plasma torches are based on DC technologies which can be transferred arc or non-transferred arc, with graphite electrodes or based on the TwinTorch™ system, wherein, two transferred arc torches are of opposite polarity connected in series [117, 118]. These different torches represent the basis of all the different waste treatment devices proposed by Tetronics. The advantage of TwinTorch™ system is the electrodes in graphite which can be adjusted in function of their erosion. However, the investment cost for this technology is expensive due to the use of a DC power supply (fragile technology with frequent maintenance). Tetronics is the plasma torch supplier of Advanced Plasma Power which has several projects of plasma gasification of MSW in UK.

For around 10 years, 100 kW DC plasma torches are widely used in China for pulverized-coal boiler burners (Guodian plasma torches). Their technology is very similar to the Messerle first-generation plasma ignition system [132]. Oral statements of industrial representatives claim that over 400 systems are in operation in China, but not for gasification, mainly due to the limited lifetime of the electrode (less than 100 hours).

RF Torches

Applied Plasma Technologies (APT) is working on the development of high power hybrid RF + DC plasma torches [133-141]. Like many researchers, it appears to them that a major

shortcoming of DC plasma torches is the short lifetime of the cathode and think RF technology is the solution to solve this major problem. Currently, they have developed a hybrid plasma torch (RF + DC) that has good energy efficiency (between 80 % and 95 %) for a power of 150 kW [140]. It is sure that this technology has, on the one hand, the great advantage of not having electrode erosion, but, on the other hand, has a very limited power with high investment costs. APT is currently working on developing a 1 MW torch but is still faced with power limitation and the expensive cost of the RF technology.

AC Torches

Some non-transferred 3-phase AC plasma torches used for waste, biomass or coal processing have been described by the IEEP team (Institute for Electrophysics and Electric Power - Russian academy of sciences) in several papers [32, 85, 86, 105-112]. The electrodes consist of water-cooled copper tubes, and the movement of the arc attachment using the self-magnetic field of the current in the electrodes (rail gun effect) minimizes erosion. This plasma torch has been designed to work on oxidizing media. A new AC plasma torch for gasification has recently been developed and can work with steam as plasma gas. The plasma torch is able to work stationary on air with electrical power from 100 kW to 600 kW. Electrode erosion is again the weakness of this technology whose the electrodes lifetime is limited to 200 hours.

An original semi-industrial scale plasma technology using a three-phase AC source is presently working at the "Centre Procédés, Energies Renouvelables et Systèmes Energétiques" – PERSÉE – MINES ParisTech in Sophia-Antipolis, France. This technology has been developed initially for the synthesis of carbon nanoparticles like fullerenes, carbon blacks, nanotubes and others. This technology has evolved since 1993 and has reached a high level of reliability, unique at this scale [142, 143].

The operating principle is as follows: plasma gas is introduced through the upper part of the plasma torches and surrounding of the graphite electrodes. An electrical arc is initiated between the three graphite electrodes, each electrode being supplied by one phase of the three-phase AC power supply. The main characteristics of the power supply are summarized in Table 7**.** The electrodes, alternatively anode and cathode, are the points of attachment of the arcs. The plasma generated consists of free arcs rotating with the frequency of the current.

The 3-phase AC plasma Torch (TAT) has some similarities with electrometallurgy technologies, e.g. electric arc furnaces for steelmaking and submerged arc furnaces for silicon

metal and ferrosilicon production. It allows large high temperature volumes and long residence times so, it is particularly adapted to the waste gasification.

Contrary to three-phase arcs commonly found in metallurgical applications, there is not a neutral point in this developed system. Thus, the arcs move freely interacting mutually by electromagnetic forces. This electromagnetic interaction leads to a global motion in the centrifugal direction [144, 145].

In the case of the gasification process, it is necessary to protect the electrodes which are in graphite, from the oxidative medium. The graphite electrode erosion can be minimized by using a sheathing gas.

Some companies are working on plasma gasification of waste such as InEnTec or PEAT but no communication is done on the technology of the plasma torches used in their plasma processes marketed as well as on their power. All their communications are based on the gasification process performances in terms of quantity of waste processed and output electrical power. In general, the gasification processes proposed are mainly based on the use of plasma torches for the vitrification of solid residues obtained after waste gasification and for the refining of the crude syngas obtained after waste gasification in the aim to have a high purity syngas, necessary for their end-use in high conversion energy processes such as gas turbines or fuel cells, or for the production of synthesis fuel.

The current market for waste plasma gasification plants is shared by some companies including Alter NRG (Westinghouse subsidiary), CHO-Power (Europlasma subsidiary), Advanced Plasma Power (APP), InEnTec, Hitachi Metals Ltd., Plasco Energy Group Inc., EnviroParks Limited [146], Sunbay Energy Corporation [147], Green Power Systems, Pyrogenesis [94, 130, 148-150], PEAT...

In Tables 8 and 9 are listed the main plants for waste gasification by plasma currently in operation around the world and the numerous plant projects for APP, Alter NRG and CHO Power. Presently, the technical feasibility and economical viability of plasma vitrification technologies have been demonstrated for a large range of hazardous wastes but it is not totally the case of plasma gasification technologies for the disposal of MSW at an industrial scale. This is a growing market and the efficiency of the waste gasification by plasma seems to be validated but the economic viability of this technology must be proven before to be accepted by the industry [4, 68, 151-160].

However, plants currently installed are of medium size (few MW of electricity produced by plant). They are mainly demonstration units to promote plasma technology for waste gasification. The proposed technologies appear fully functional but it seems that the limit of

installed plants is mainly due to power limitations of plasma torches and DC power supplies available on the market (around one MW) and their high investment cost and maintenance cost. Presently, most of the gasification technologies are based on DC plasma torches. Although widely used, these technologies have strong technical and economic constraints mainly related to their lack of robustness and reliability and their equipment and operating costs relatively high due to their frequent and expensive maintenance: (i) short lifetime of the electrodes (between 300 h and 500 h) [98], (ii) sensitive electronics. Indeed, the technological complexity of the power supplies of the DC torches involves a costly price, mainly due to the rectifier part of the electrical signal that can involve an increase of 30 % of the price of the power supply. Moreover, the limited autonomy of the metal electrodes implies high operating costs. AC power supplies could be an alternative for reducing costs. They have proven their durability and reliability for many years in the steel industry with investment cost and maintenance cost much cheaper for few MW. For the future development at industrial scale of the Waste-to-Energy gasification processes based on thermal plasma, it appears that it will be mandatory to overcome these limitations of robustness as well as to significantly reduce equipment and operating costs. Plasma torches based on cheap consumable parts like graphite electrodes can avoid their water cooling, making this plasma technology less complex and more reliable and could be a solution to the problems of reliability and equipment/operating costs for the development of the plasma gasification at industrial scale.

From the perspective of life cycle assessment of three different technologies of thermal plasma generator (Radio-frequency plasma system – RF, microwave-induced system – MW and plasma torch system – PT) in comparison of downdraft gasifier system – DG, a recent comparative study of Shie et al. [160] on the overall thermal efficiency – ηE, the energy return on investment – EROI and the net energy ratio – NER, indicate the highest efficiency of the PT technology in all the cases with a ηE of 84.07 % (64.11 % for DG, 38.59 % for MW and 57.03 % for RF), with a NER of 7.86 (5.79 for DG, 3.13 for MW and 5.01 for RF) and an EROI of 8.86 (6.79 for DG, 4.13 for MW and 6.01 for RF). These terms, according to the authors, are more representative than the price of production which is influenced by the markets.

Conclusion

In this review, where are compared the performances of the different waste gasification processes based on thermal plasma represented in the scientific literature, the main

conclusions are that plasma technology appears to be one of the most probative technologies for the processing of waste-to-energy and can be easily adapted to the treatment of various wastes (municipal solid wastes, heavy oil, used car tires, medical wastes …). Allothermal gasification allows processing all kind of wastes (domiciliary and industrial wastes) by adjusting the energy input with the plasma, independently of the oxidizing agent ratio, the LHV and the moisture of the waste.

About the comparison of chemical efficiency of allothermal versus autothermal gasification processes: (i) the values of cold gas efficiency (energy efficiency) are in the same order of magnitude, (ii) the main difference is on the net electrical efficiency of the overall process. This value is based on the theoretical electrical conversion performances of the end-use devices which are strongly dependent of the tar content in the syngas, key parameter for the performances of the overall process. The high enthalpy, the residence time and high temperature in plasma can advantageously improve the conditions for gasification, which are inaccessible in other thermal processes and can enhance strongly the degradation of the tars and allow reaching, due to low tar content in the syngas, better net electrical efficiency than autothermal processes.

Concerning the advantages of the waste gasification by thermal plasma, the role of the plasma treatment is twofold: it allows, on the one hand, a significant purification of gas by limiting the production of tars and on the other hand, producing a synthesis gas enriched in hydrogen (water-gas shift reaction). Plasma methods have also the advantages to be able to operate at high temperature and to be retrofitted to existing installation. Such a temperature in plasmas can allow synthesizing or degrading chemical species in some conditions unreachable by conventional combustion and can greatly accelerate the chemical reactions. Thermochemistry of combustion does not allow precise control of the enthalpy injected into the reactor. Plasma process allows an easiest enthalpy control by adjusting the electrical power. The reactive species produced by the plasma, such as atomic oxygen and hydrogen or hydroxyl radicals, is an additional advantage for the use of plasma and enhance strongly the degradation of the tars with greater efficiency than conventional processes.

Concerning the development and the operation of the plasma technologies on the energy market, presently, the technical feasibility and economical viability of plasma vitrification technologies have been demonstrated for a large range of hazardous wastes but it is not totally the case of plasma gasification technologies for the disposal of MSW at an industrial scale. This is a growing market and the efficiency of the waste gasification by plasma seems to be validated but the economic viability of this technology must be proven before to be accepted

by the industry. Presently, the strong expansion in the world of numerous plasma gasification plants (projects and operational plants) shows clearly that a step has been taken and in the future, plasma gasification will play a significant role in the field of renewable energy.

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List of Tables

Table 1 Main chemical reactions of gasification

N°	Reaction name	Chemical reaction	Reaction enthalpy ΔH [(1)]
(1)	$C_nH_mO_k$ partial oxidation	$C_nH_m + {}^{n}/_{2}\ O_2 \leftrightarrow {}^{m}/_{2}\ H_2 + n\ CO$	Exothermic
(2)	Steam reforming	$C_nH_m + n\ H_2O \leftrightarrow (n + {}^{m}/_{2})\ H_2 + n\ CO$	Endothermic
(3)	Dry reforming	$C_nH_m + n\ CO_2 \leftrightarrow {}^{m}/_{2}\ H_2 + 2n\ CO$	Endothermic
(4)	Carbon oxidation	$C + O_2 \rightarrow CO_2$	-393.65 kJ.mol^{-1}
(5)	Carbon Partial oxidation	$C + ½\ O_2 \rightarrow CO$	-110.56 kJ.mol^{-1}
(6)	Water-gas reaction	$C + H_2O \leftrightarrow CO + H_2$	+131.2 kJ.mol^{-1}
(7)	Boudouard reaction	$C + CO_2 \leftrightarrow 2\ CO$	+172.52 kJ.mol^{-1}
(8)	Hydrogasification	$C + 2\ H_2 \leftrightarrow CH_4$	-74.87 kJ.mol^{-1}
(9)	Carbon monoxide oxidation	$CO + ½\ O_2 \rightarrow CO_2$	-283.01 kJ.mol^{-1}
(10)	Hydrogen oxidation	$H_2 + ½\ O_2 \rightarrow H_2O$	-241.09 kJ.mol^{-1}
(11)	Water-gas shift reaction	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41.18 kJ.mol^{-1}
(12)	Methanation	$CO + 3\ H_2 \leftrightarrow CH_4 + H_2O$	-206.23 kJ.mol^{-1}

[(1)] T = 298 K, P = 1.013 10^5 Pa, carbon as solid and water in vapor form

Table 2 Tar and solid particles rates in the gasification raw-gas in function of the reactor configuration

Reactor	Tar rates, g.Nm^{-3}			Solid particles rates, g.Nm^{-3}		
	Min	Max	R.R.	Min	Max	R.R.
Updraft	1	150	20 – 100	0.1	3	0.1 – 1
Downdraft	0.04	6	0.1 – 1.2	0.01	10	0.1 – 0.2
Fluidized bed	< 0.1	23	1 – 15	1	100	2 – 20

R.R.: Representative Range in which are most of the processes studied

Table 3 Performances of plasma gasification from scientific literature and comparison versus autothermal gasification

Plasma Torch	Ref.	Waste	LHV $MJ.kg^{-1}$	Oxidizing agent	Power kW	Syngas $Nm^3.kg^{-1}$	H_2 Vol%	CO Vol%	LHV $MJ.Nm^{-3}$	η %	Net electrical efficiency, %
DC	[81]	Wooden Sawdust	-	$CO_2 + O_2$	95 – 153	1 – 1.9	22 – 46	44 – 68	-	-	-
	[25]	Tires	37.33	H_2O	35.2	-	24.12	14.17	8.96	-	-
	[74]	Polypropylene	-	H_2O	35.2	2.17	27.06	13.33	-	-	-
	[94]	MSW	-	H_2O + air	-	-	8 – 14	20 – 29	4.1 – 5.2	-	-
	[94]	Hazardous Waste	-	H_2O + air	-	-	28.3	18.8	6.0	-	-
	[92]	MSW/tires mix	13.95	O_2	3,22	1.10	22.62	40.46	11.9	79	28 – 46 #
AC	[32]	Wood residues	13.9	Air	2.16+	2.45	28	23.6	13.5	84	29 – 49 #
	[85]	Wood	16	None	3.6 +	2.48	24.5	31.4	6.16	78	28 – 46 #
	[85]	RDF *	15	None	3.82 +	2.46	26.3	27.5	5.88	77	27 – 45 #
	[85]	Tires	33	H_2O	6.66 +	5.03	30.6	24	5.89	75	26 – 44 #
Autothermal	[9]	MSW	7 – 18	Air – O_2	-	-	-	-	4 – 7	50 – 80	15 – 24

* The refused derived fuel (RDF) terms the specially prepared dry fuel consisting of chips of wood, paper, plastic, fabric, rubber and other hydrocarbons.

+ Energy in MJ for 1 kg of waste

With electrical conversion efficiency of around 0.35 for steam thermodynamic cycle [32] and around 0.59 for the combined cycle [37]

Table 4 Properties of the Westinghouse DC Torches

Model	Power kW	Diameter In	mm	Length In	mm	Weight lb	kg
Marc 3a	80 – 300	3.5	89	32.5 mini	826 mini	27	12.2
Marc 3HC	5 – 150	3.5	89	20.2 mini	513 mini	16.6	7.5
Marc 11L	300 – 800	18	457	35	889	450	204
Marc 11H	700 – 2400	18	457	35	889	450	204

Table 5 Main technical characteristics of the Europlasma DC Torches

Model	Power, kW	Plasma Gas
Hot Cathode	25 – 100	Ar, He, H_2
Cold Cathode	100 – 300	Air, CO, CO_2
Cold Cathode	300 – 800	Air
Cold Cathode	800 – 2000	Air
Cold Cathode	1500 – 4000	Air

Table 6 Main technical characteristics of the PSC DC Torches

Model	Power, kW
PT50	10 – 100
PT150	100 – 300
PT200	200 – 900
PT250	800 – 3000
PT255	1500 – 3000

Table 7 Technical specifications of the 3-phase AC power supply

Input	380V 50hz 3-phase
Max. Output Voltage	0-500 V 3-phase
Max. Output Current	0-400 A
Max. Output Power	263 kVA
Output frequency	84, 168, 338 or 675 Hz

Table 8 Main plants for waste gasification by plasma currently in operation around the world and plant projects for the next years [114-116, 119-131, 147-148]

Location	Raw material	Capacity (TPD)	Start Date	Production	Plasma Technology	Company
Mihama-Mikata, Japan	MSW/WW Sludge	25	2002		DC, Westinghouse	Hitachi Metals Ltd.
Utashinai, Japan	MSW/ASR	300	2002		DC, Westinghouse	Hitachi Metals Ltd.
Yoshi, Japan	MSW	151	1999		DC, Westinghouse	Hitachi Metals Ltd.
Pune, India	Hazardous Waste	68	2009	1,6 MWe	DC, Westinghouse	Maharashtra Env. Pow.
Nagpur, India	Hazardous Waste	68	2010	1,6 MWe	DC, Westinghouse	Maharashtra Env. Pow.
Shanghai, China			Project		DC, Westinghouse	
Tallahassee, USA	MSW	910	Project	35 MWe	DC, Westinghouse	Green Power Systems
Morcenx, France	Industrial/Biomass	137	2012	12 MWe	DC, Europlasma	CHO-Power
Hull, Sunderlan, Barry & Barrow, UK	Industrial/Biomass	107 x 4 plants	Project	37.5 MWe	DC, Europlasma	CHO-Power
Port Hope, Canada	MSW/TDF	400	Project	26 MWe	DC, Europlasma	Sunbay Energy Corp.
Hirwaun, UK	MSW/industrial	~750	Project (2015)	20 MWe	DC, Europlasma	EnviroParks Limited
Ottawa, Canada	MSW	85	Demonstration facility	1 MWe/ton	DC, PSC	Plasco Energy Group Inc.
Trail Road, USA	MSW		Demonstration facility	0.88 MWe/ton	DC, PSC	Plasco Energy Group Inc.
Los Angeles, USA	MSW		Project		DC, PSC	Plasco Energy Group Inc.
Beijing, China	MSW	200	Project		DC, PSC	Plasco Energy Group Inc.
Tainan City, Taiwan	Hazardous Waste	3-5	2005		DC, Homemade	PEAT International
Iizuka, Japan	Industrial Wastes	10	2004		DC, Homemade	InEnTec
U.S. Navy	Shipboard Wastes	7	2004		DC, Pyrogenesis	Pyrogenesis
Hurlburt Field, USA	MSW/Hazardous	10.5	2011		DC, Pyrogenesis	Pyrogenesis
Faringdon, UK			Demonstration facility		DC, Tetronics	Advanced Plasma Power
Swindon	MSW	91,000 t/year	2008	16.3 MWe	DC, Tetronics	Advanced Plasma Power
South Wales	MSW		Project		DC, Tetronics	Advanced Plasma Power
North of England	MSW		Project		DC, Tetronics	Advanced Plasma Power
South West England	MSW		Project	17 MWe	DC, Tetronics	Advanced Plasma Power
Scotland – East Coast	MSW	91,000 t/year	Project		DC, Tetronics	Advanced Plasma Power
Brazil	MSW		Project		DC, Tetronics	Advanced Plasma Power
Brazil	ASR		Project		DC, Tetronics	Advanced Plasma Power
Belgium	Landfill	246 x 5 plants	Project	100 MWe	DC, Tetronics	Advanced Plasma Power
Swindon	Residual wastes		Demonstration facility	BSNG	DC, Tetronics	Advanced Plasma Power

ASR: Auto Shredder Residue, WW Sludge: Waste Water Sludge, TDF: Tire Derived Fuel, BSNG: Bio Substitute Natural Gas, TPD: Metric Tons Per Day

Table 9 Waste gasification project using Alter NRG's plasma technology at various stages of development (Q1 2011) [120]

COUNTRY	PRODUCTION	Site Selection	Feasibility Study	Feedstock Agreement	Initial Engineering	Regulatory Application	Regulatory Approval	Financing	Detailed Engineering	Construction,	Commissioning / Start-up	Operation
NORTH AMERICA												
SE, US	Biomass-to-Ethanol											
St. Lucie, FL	WTE											
Atlantic City, NJ	WTE											
Milwaukee, WI	WTE											
Ontario, Canada	WTE											
Minnesota	WTE repowering											
Madison, PA	Biomass-to-Ethanol											
US – Strategic Licensor	WTE (3 projects)											
EUROPEAN UNION												
Poland	WTE											
Spain	WTE											
United Kingdom	WTE											
Spain	Industrial/hazardous											
Italy	Medical Waste											
INDIA												
India	Hazardous WTE (3-5 proposed facilities)											
Pune	Hazardous WTE											
Nagpur	Hazardous WTE											
CHINA												
Central China	Biomass-to-Ethanol (150 known projects)											
Western China	WTE											
Central China	WTE											
Southern China	WTE (2-5 projects – various stages)											
AUSTRALIA												
Melbourne	Waste-to-ethanol											
Geelong	Waste-to-energy											
Kwinana	Waste-to-energy											
RUSSIA												
Moscow	WTE (5 projects)											